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New distribution data of the Mosor rock lizard (*Dinarolacerta mosorensis*): a review of its range and conservation status

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Abstract

The Mosor rock lizard, *Dinarolacerta mosorensis* (Kolombatović, 1886), is an understudied lacertid species. It is geographically isolated within the Dinaric Alps and is categorized as Near Threatened on the IUCN Red List. Historical and newly collected records were evaluated to assess the distribution, range, and conservation status of the Mosor rock lizard. Our results show that most range localities and suitable habitats are found in Bosnia and Herzegovina and Montenegro, whereas Croatia comprises less than 2% of the total global range. We extended the species' range further north and reconfirmed its presence west of the Neretva River. In total, we identified 33 localities—encompassing mountains, canyons, and plateaus—of which nine are new. The maximum elevation at which the species has been documented is 2,031 m a.s.l., with 91% of records occurring above 1,000 m a.s.l. The Area of Occupancy (AOO), calculated using 2 × 2 km grids, is 528 km², whereas the Extent of Occurrence (EOO) is estimated at 18,725.34 km². Despite significant variation in protected area coverage among countries, 44% of the species' known AOO is within protected areas. Given that global climate change is the main threat to this species, there is an urgent need for targeted data collection and improved management strategies to ensure its long-term protection.

Key Words

Area of Occupancy, Dinaric Alps, endemic species, Extent of Occurrence, petrophilous, protected areas, threats

Introduction

The Dinaric Alps are home to numerous endemic and stenoendemic species, shaped by complex biogeographical processes and glacial periods. These mechanisms have contributed to the fragmented distribution patterns observed across multiple taxa (Đurović et al. 2021). One such species is the Mosor rock lizard, *Dinarolacerta mosorensis* (Kolombatović, 1886), a cold-adapted stenoendemic reptile with a fragmented distribution across mountainous regions of Croatia, Bosnia and Herzegovina, and Montenegro (Džukić 1989; Ljubisavljević et al. 2016). This species is one of two in the genus *Dinarolacerta*, the other being *D. montenegrina* Ljubisavljević, Arribas, Džukić & Carranza, 2007, found in Montenegro and Albania (Petrov 2006; Ljubisavljević et al. 2007a, 2016).

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The Mosor rock lizard is primarily associated with rocky montane terrains and is usually found on limestone outcrops above the tree line or within open forest (Džukić 1991; Arnold and Ovenden 2004; Speybroeck et al. 2016). The species thrives at higher elevations (1,100–1,900 m), being present at lower elevations only in canyons and along mountain slopes in the Adriatic hinterland (Ljubisavljević et al. 2024). According to the literature, the lowest documented occurrence is at 270 m a.s.l. in the Mrtvica River Canyon (Montenegro), which is likely relictual (Ljubisavljević et al. 2016). The highest confirmed record is at Lomno Ždrijelo on Mt. Durmitor (Montenegro), at 1,900 m a.s.l. (Džukić 1991; Ljubisavljević et al. 2016). Literature records below 1,000 m a.s.l. remain rare. In Montenegro, examples include Herceg Novi – Kameno Brdo (450 m a.s.l.; Džukić 1989), and in Bosnia and Herzegovina, Mt. Baba, Ključ Valley (960 m a.s.l.; Arnold 1987). Other records from Croatia include Mt. Kozjak (580 m a.s.l.; Hunt 1957), Mt. Biokovo (Krljava, 700–800 m a.s.l.; Džukić 1989), and Mt. Mosor (750 m a.s.l.; Mekinić 2010; 900–1,000 m a.s.l.; Džukić 1989).

A phylogeographical study suggests that the species' fragmented distribution is a remnant of a formerly wider and continuous range during colder periods and that it now occupies interglacial refugia (Podnar et al. 2014). Despite its restricted range and specific ecological requirements, detailed distributional data remain scarce. Most known localities were recorded in the late 19th and early 20th centuries. The first distributional overview was compiled by Bischoff (1984), and the most comprehensive review was conducted by Džukić (1989, 1991). Since then, the species' known range in Croatia and Bosnia and Herzegovina has remained largely unchanged, with the exception of a record from Mt. Prenj in Bosnia and Herzegovina, which represents the species' northernmost known occurrence (Šunje et al. 2014). A distribution update for Montenegro was published nine years ago (Ljubisavljević et al. 2016). Literature records west of the Neretva River are scarce. For a long time, the only confirmed localities were Mt. Mosor and Mt. Biokovo, along with one reported finding (De Luca, pers. comm.) that lacked a specific location (Džukić 1991; Ljubisavljević et al. 2007a).

The species is listed in Annex III of the Bern Convention (Council of Europe 1979) and in Annexes II and IV of the EU Habitats Directive (92/43/EEC) (Council of the European Union 2013). It is strictly protected under the Law on Nature Protection (NN 80/13, 15/18, 14/19, 127/19) in Croatia. In Montenegro, it is protected under the Decision on the Protection of Rare, Declining, Endemic, and Endangered Plant and Animal Species (Official Gazette of the Republic of Montenegro 2006). However, in Bosnia and Herzegovina, protection is partial. Under the Regulation on Strictly Protected and Protected Wild Species (Official Gazette of the Republic of Srpska No. 65/20), *D. mosorensis* is classified as a protected wild species. In contrast, the species is not protected in the Federation of Bosnia and Herzegovina (Federalno ministarstvo okoliša i turizma 2020; Government of the Republic of Srpska 2020).

The species is classified as "Near Threatened" in the current IUCN Red List assessment for Europe, which covers its entire range, and as "Endangered" within the EU27, which includes only Croatia (Crnobrnja Isailović et al. 2024). The primary reasons for this classification in Europe are the species' extent of occurrence being below 16,000 km² and a continuing decline in habitat quality in at least part of its range (Crnobrnja Isailović et al. 2024). However, it remains unclear whether the population is severely fragmented or whether habitat decline is extensive enough to justify the recognition of ten or fewer locations (Crnobrnja Isailović et al. 2024).

For the EU27 (Croatia), the identified threats include diverse human-related impacts at three known locations, along with ongoing habitat degradation and loss. These factors contribute to a continued decline in habitat quality and extent and, by inference, in the number of mature individuals (Crnobrnja Isailović et al. 2024). The species' range in Croatia is estimated at 1,528 km², representing 10% of its European distribution (Crnobrnja Isailović et al. 2024).

The national Red Lists of Croatia, the Federation of Bosnia and Herzegovina, and Montenegro classify the species as "Vulnerable" (Đug et al. 2013; Jelić et al. 2015, 2023; Lelo et al. 2016). However, the species has not been assessed in the Republic of Srpska (the other entity in Bosnia and Herzegovina) (Vlada Republike Srpske 2012).

This article aims to present unpublished data and summarize existing published records to update the known range and distribution of this endemic and relict species. Specifically, we present (1) a new distribution map, (2) a range analysis with polygon-defined localities, (3) a conservation status review based on Red List criteria, including Extent of Occurrence (EOO) and Area of Occupancy (AOO), and (4) an assessment of protected area coverage across the species' range.

Materials and methods

Distribution and range

Our study area includes the Dinaric Alps region in the three countries where *D. mosorensis* is present. To review the species' range and distribution, records up to 2024 have been gathered from various sources, including literature, open project reports, the database Biologer (Popović et al. 2020), and unpublished data from the authors and their colleagues. We followed all the terms, licenses, and conditions of the open-access database Biologer. The presence data were preprocessed before subsequent analysis. Initially, we eliminated literature entries with general locations (e.g., Dalmatia or Herzegovina) and discarded duplicate observations. All the literature data that lacked coordinates were georeferenced using 1:25,000 topographic maps. The altitude data for the localities were gathered from the literature when available, and if not, were calculated from a Digital Elevation Model in

ArcGIS Pro (v. 3.4, ESRI). The occurrence data used to perform all analyses in this study are in Suppl. material 1.

Alongside the collection of literature data, targeted fieldwork has been undertaken between 2018 and 2024 in all three countries. Fieldwork targeted suitable habitats, including potential refugial habitats in gorges and canyons at lower altitudes (Ljubisavljević et al. 2016). The goal was to confirm old and find new localities, thus enhancing the dataset's accuracy and comprehensiveness. The coordinates were taken in the field using the WGS84 coordinate system.

We classified occurrence records into two groups: literature and new data, further categorizing them by country. Coordinates were designated as georeferenced from literature or original sources. Records were then grouped into range localities (broader areas defined by geographic toponyms like mountains, plateaus, or river canyons) and specific locations within these, corresponding to precise sites of species detection.

A range map was generated in ArcGIS Pro 3.4, incorporating all confirmed species locations overlaid on Digital Elevation Model maps. Range polygons for each locality were primarily delineated using the 1,000 m a.s.l. contour as a baseline, given that 91% of records were documented above this elevation. For the few locations below this altitude, polygon borders were manually expanded to include these lower-elevation records. Additionally, a distribution map was created in ArcGIS Pro 3.4 using coordinates, range polygons, and the standard 10 × 10 km EEA reference grid cells. The use of this grid follows the European Environment Agency's standard for expressing distribution and range when reporting on the conservation status of species and habitats under the Habitats Directive (DG Environment 2017).

To establish the species' range as accurately as possible with this dataset, we used two methods. First, the surface area of each range polygon was calculated and summarized for the whole area and for each country separately. Second, the number of 10 × 10 km grid cells was counted for the entire area and each country, and their total surface area was calculated. These results were not used for the IUCN species' status assessment.

Conservation status according to the Red List criteria

The species` conservation status was re-evaluated using the IUCN Red List Categories and Criteria methodology (IUCN Standards and Petitions Committee 2024). All parameters used for the conservation status assessment, including EOO and AOO, were calculated strictly following the instructions defined by the IUCN (IUCN Standards and Petitions Committee 2024).

EOO represents the area defined by the shortest continuous imaginary boundary of the present occurrence of a taxon. It was measured by a minimum convex polygon with no internal angle exceeding 180 degrees (IUCN Standards and Petitions Committee 2024). This was determined in a geographic information system (GIS), after importing the records, by joining the outermost occurrence points and calculating the resultant polygon's surface area. AOO represents the area of suitable habitat currently occupied by the taxon within its EOO. We estimated AOO using the 2 × 2 km grid cells (IUCN Standards and Petitions Committee 2024).

According to IUCN guidelines (IUCN Standards and Petitions Committee 2024), EOO is a parameter that measures the spatial spread of the areas currently occupied by the taxon and thus also the degree to which risks from threatening factors are spread spatially across the taxon's geographical distribution. We compared our data and estimates for EOO and AOO with the latest global and country-level species assessments. We also addressed other aspects of the assessment criteria where we have identified discrepancies related to our field observations or post-data collection.

Protected areas important for the species conservation

Nationally designated protected areas (NPAs) and the Natura 2000 network (located only in EU member country Croatia) were analyzed to assess their size and importance for the species' future survival. Montenegro and Bosnia and Herzegovina are EU candidate countries (European Union 2025) and have already incorporated the foundations for establishing an ecological network into their Nature Protection Acts. It is expected that the network will be fully implemented upon their official membership entry (Vlada Federacije Bosne i Hercegovine 2011; Vlada Republike Srpske 2024).

To calculate the total surface area under current legal protection where the species is present, we used AOO. The 2 × 2 km grid cells were overlaid with the GIS layer of protected areas for Croatia (available from BIOPORTAL, https://www.bioportal.hr/gis/), Montenegro (available from "Portal otvorenih podataka," https://data.gov.me/dataset/zasticena-podrucja-prirode-crnegore), and Bosnia and Herzegovina (data acquired from relevant public authorities). Next, AOO grid cells that intersected with protected areas were selected, and their total surface area was calculated.

Results

Distribution and range

A total of 211 records were gathered from 1886 to 2024, comprising 95 literature and 116 new data records (Fig. 1). The species is now confirmed at 33 validated range localities, with one potential locality (Sinj) pending further validation and two localities disproved (above Cetinje and Kozjak/Opor). Nine are new range

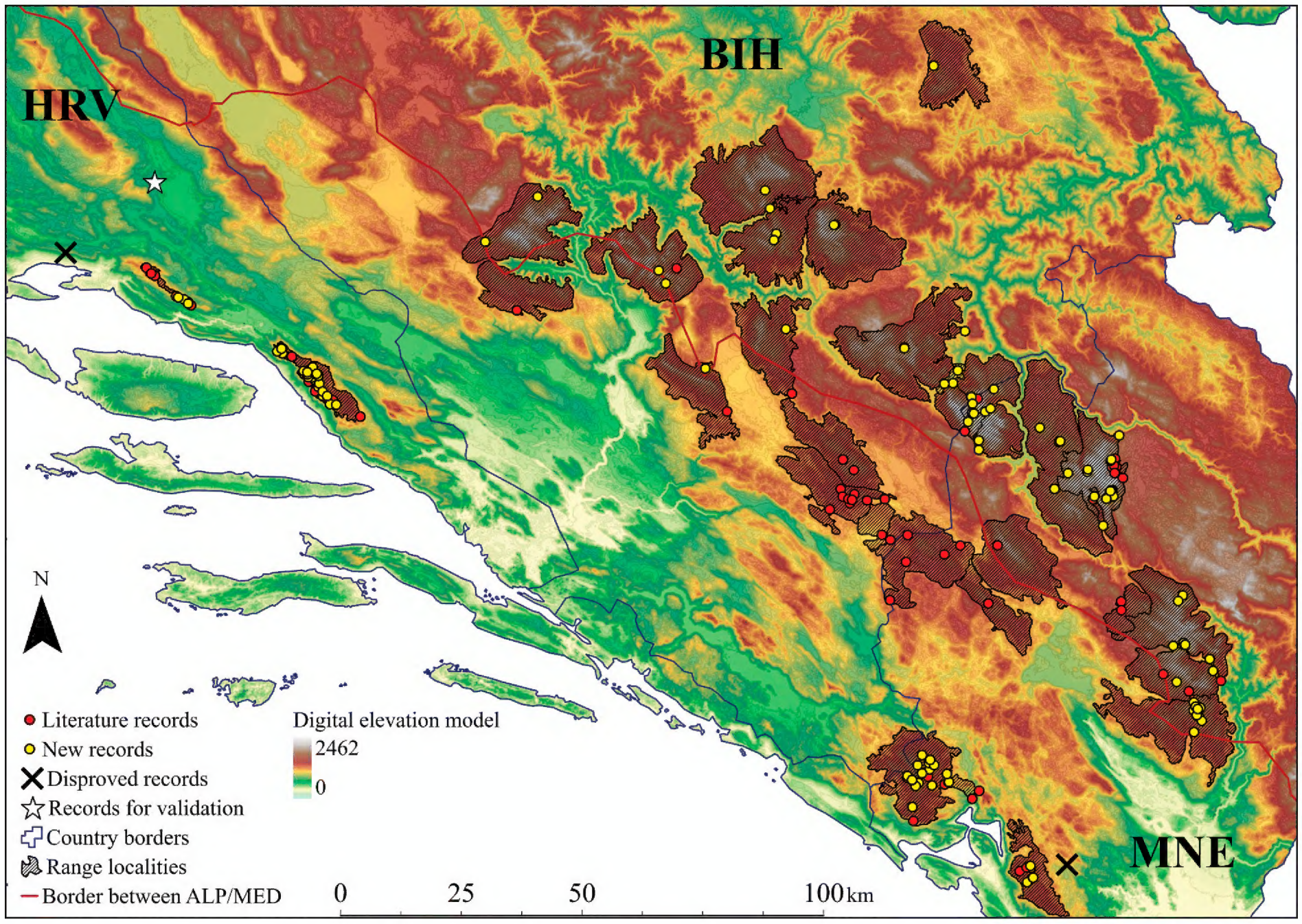

Figure 1. Distribution map of *Dinarolacerta mosorensis*, showing literature-based records (red) and newly recorded locations (yellow), including one record requiring further validation and two disproved records. The map covers three countries (HRV—Croatia, BIH—Bosnia and Herzegovina, and MNE—Montenegro) and two biogeographical regions (ALP—Alpine and MED—Mediterranean).

localities, here reported for the first time: Mt. Čvrsnica, Mt. Bjelašnica, Mt. Visočica, Mt. Treskavica, the Rakitnica Canyon, Mt. Romanija, the Sutjeska Canyon, Mt. Bioč, and the Morača Mountains (Fig. 2). A total of 179 specific locations were recorded within these 33 range localities. The distribution and range of the species have expanded across its entire known area. The total range of the species, which includes all range localities defined by polygons (areas above 1,000 m a.s.l., as well as the localities in canyons that are slightly lower), covers an area of 5,014.36 km² (Fig. 2). Alternatively, using 10 × 10 km EEA reference grid cells, there are 55 grid cells, totaling 5,500.00 km² (Fig. 3). Most of the records (91%) are located above 1,000 m a.s.l.

Croatia

The new data do not reveal additional range localities in Croatia. They confirm the literature ones, Mt. Mosor and Mt. Biokovo, and offer a more accurate distribution by identifying new locations on these mountains (Fig. 1). The entire known distribution in Croatia is placed within seven 10 × 10 km grid cells (700 km²), representing 12.73% of the total range based on the grid cells (Fig. 3). When the range is assessed using polygons of range localities, there are only 93.55 km² where the species is present in Croatia, which constitutes merely 1.87% of the total range.

The lowest recorded occurrence in the last 20 years in Croatia was on Mt. Mosor at 750 m a.s.l., while the highest was on Mt. Biokovo at 1,683 m a.s.l. Although we visited the localities, we were unable to confirm the records for Opor—Mt. Kozjak and the NHMW museum specimens from Sinj and Troglav. During this period, we also surveyed additional locations, including Mt. Svilaja, Mt. Kamešnica, and the mountain ridges of Vrgorsko Gorje (Šibenik, Mihovil, and Matokit), but did not find *D. mosorensis* there.

Bosnia and Herzegovina

The species is now confirmed at 16 range localities (Fig. 1). The discovery of five additional sites (Mt. Bjelašnica, Mt. Visočica, Mt. Treskavica, the Rakitnica Canyon, and Mt. Romanija) has extended the species' known distribution further north (Fig. 2). Currently, the northernmost known site is Mt. Romanija, located about 65 km in a direct line from the previous one (Mt. Prenj). A new record from Mt. Čvrsnica confirms the species' presence west of the Neretva River, representing the nearest known location to Croatia. The species has been reconfirmed on Mt. Crvanj, Mt. Velež, Mt. Prenj, and Mt. Zelengora (Fig. 1).

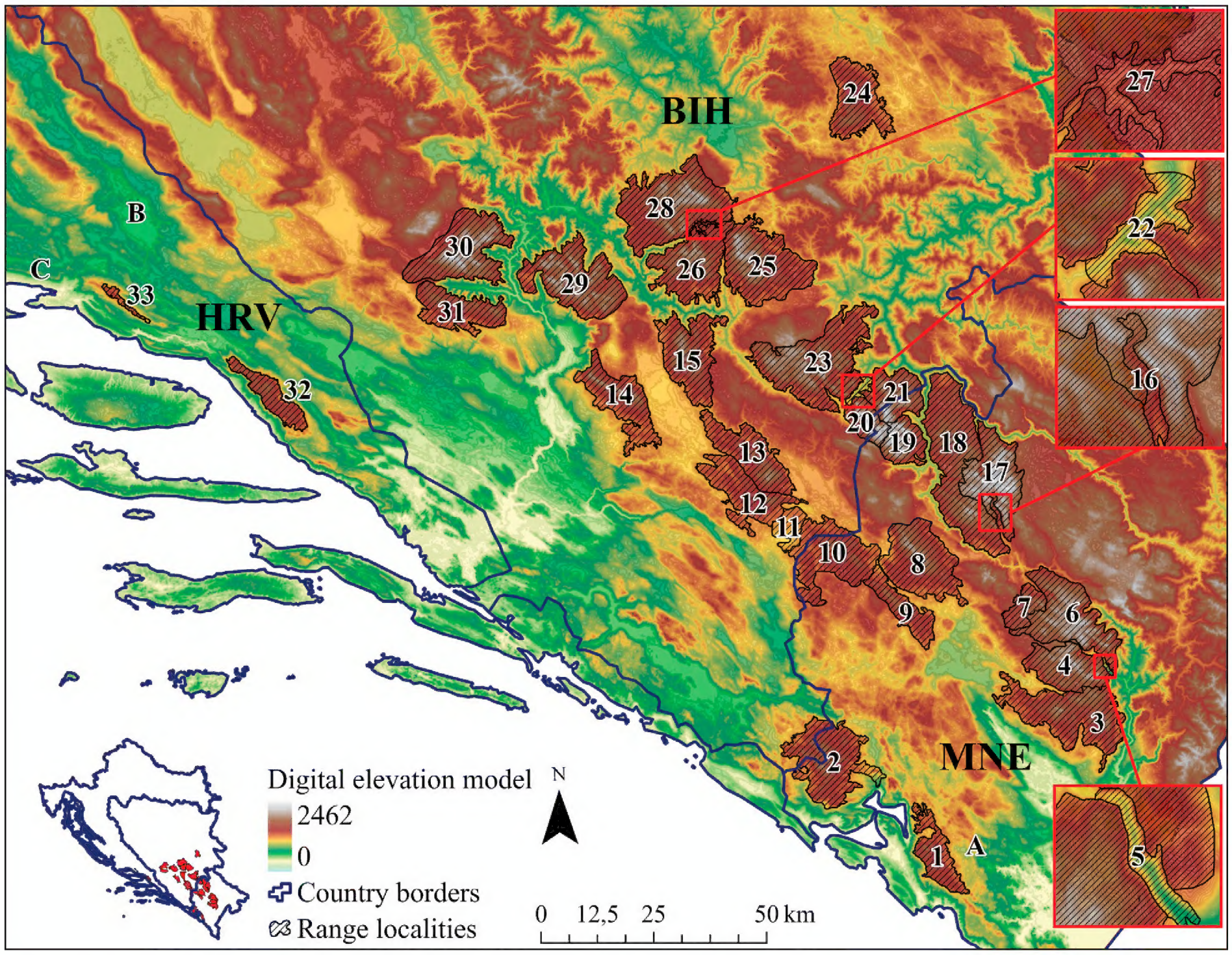

Figure 2. Range map of *Dinarolacerta mosorensis* with polygons representing areas above 1,000 m a.s.l. at confirmed sites. Each number represents one locality, and letters represent literature localities without precise data or questionable findings. Names of localities are written in Suppl. material 1.

In Bosnia and Herzegovina, the lowest recent occurrence was recorded at the new locality Sutjeska Canyon (621 m a.s.l.), whereas the highest was at Mt. Visočica (1,723 m a.s.l.). During this period, we also surveyed additional locations, including Mt. Vran, Mt. Lib, Mt. Kamešnica (on the BIH side), Mt. Šator, Mt. Klekovača, and Mt. Orjen (on the BIH side), but the species was not found. The total known distribution in Bosnia and Herzegovina falls within 25 10 × 10 km grid cells (2,500 km²), accounting for 45.45% of the species' recorded range, based on the total number of grid cells (Fig. 3). When the range is analyzed using polygons of range localities, the area where the species is present is 2,799.88 km², representing 55.84% of the total species range.

Montenegro

The updated data primarily provide a more accurate distribution of known mountains in Montenegro while also confirming two new range localities (Mt. Bioč and Mt. Morača Mountains) and reconfirming its presence on Mt. Volujak (Fig. 1).

The lowest occurrence record in Montenegro remains in the Mrtvica River Canyon at 270 m a.s.l., while the highest is now at Mt. Volujak at 2,031 m a.s.l. Mt. Lovćen remains the southernmost point of the species' distribution, whereas the Mrtvica River Canyon marks its easternmost site. During this period, we also surveyed additional locations, including Mt. Rumija, Mt. Sinjajevina, Mt. Ljubišnja, and Mt. Bjelasica, but the species was not found. The currently known distribution in Montenegro occupies 30 10 × 10 km grid cells (3,000 km²), representing 54.54% of the known range based on the grid cells (Fig. 3). When the range is analyzed using polygons of range localities, the area where the species is present is 2,120.93 km², which accounts for 42.30% of the total species range.

Conservation status according to the Red List criteria

We assessed the Extent of Occurrence (EOO) and Area of Occupancy (AOO) for the species across its entire distribution, as well as separately for each country, following IUCN methodology. The estimated total EOO for the

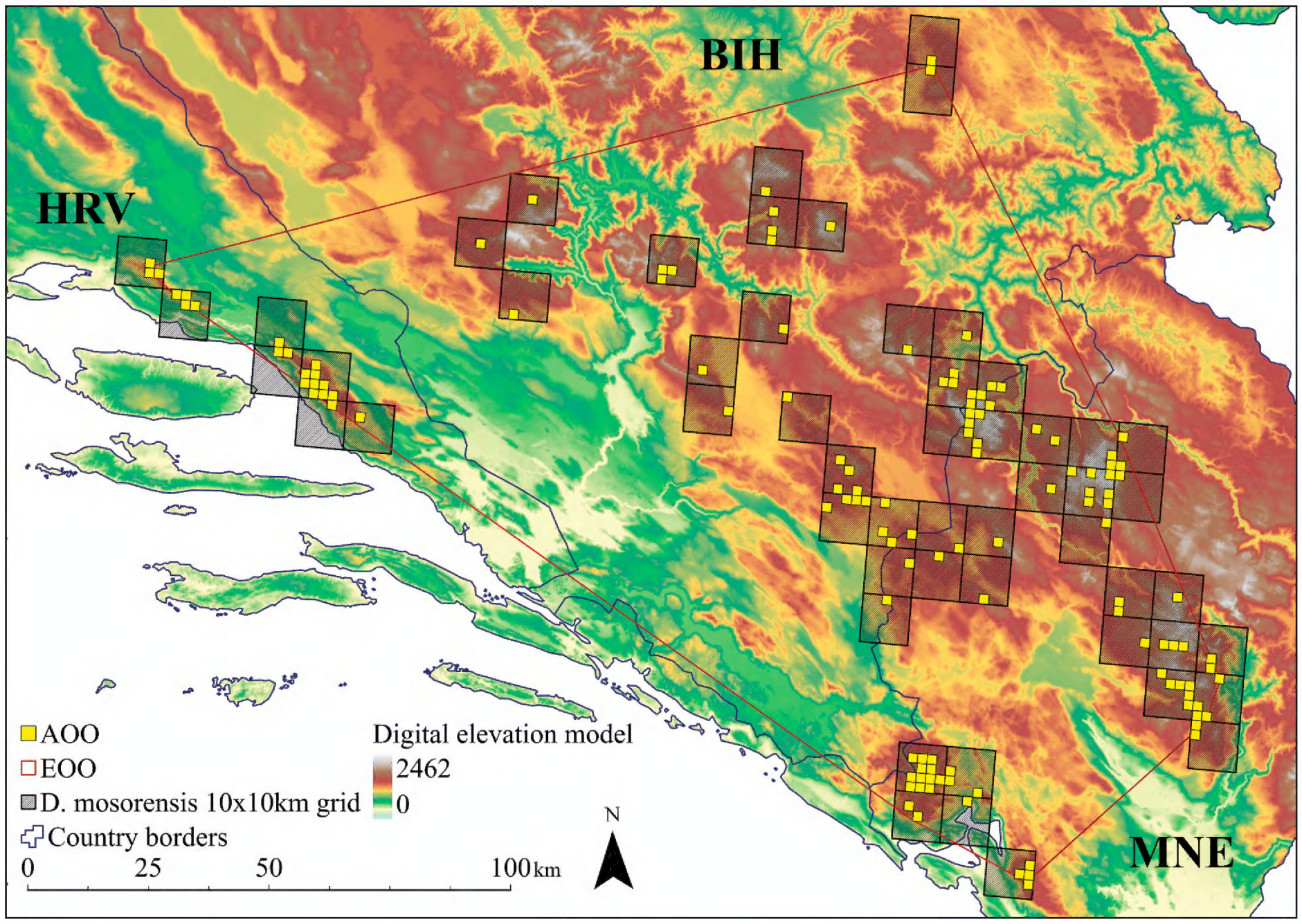

Figure 3. Geographic range of the Mosor Rock Lizard, showing the Extent of Occurrence (EOO) outlined in red and the Area of Occupancy (AOO) represented by yellow cells. The map is overlaid with the 10 × 10 km EEA reference grid.

known distribution is 18,725.34 km², whereas the AOO, determined using 2 × 2 km grid cells, is 528 km² (Fig. 3). In Croatia, the estimated EOO is 143.45 km² and the AOO is 84 km², calculated from 21 grid cells (2 × 2 km). In Bosnia and Herzegovina, the EOO is 5,773.34 km² and the AOO is 136 km², based on 34 grid cells (2 × 2 km). In Montenegro, the estimated EOO is 4,727.92 km² and the AOO is 308 km², derived from 77 grid cells (2 × 2 km). One potential locality (Sinj) and two discarded localities (above Cetinje and Kozjak) were not included in the assessment.

Protected areas important for the species conservation

The overlap between protected areas and AOO reveals that 44% of the known Area of Occupancy is within protected areas. In Croatia, all known occupancy sites are protected (100%). These two localities are part of the Natura 2000 network (HR2001352 Mosor and HR5000030 Biokovo), with Biokovo also designated as a Nature Park. In Montenegro, protected areas cover eight localities (53.3%) and 39% of occupancy grid cells. NPAs where the species is present include National Park Lovćen, Nature Park Orjen, National Park Durmitor, Nature Park Dragišnica and Komarnica, and Regional Park Piva. In Bosnia and Herzegovina, six localities (37.5%) and 26% of occupancy grid cells are protected. NPAs supporting the species include National Park Sutjeska, the nature monument "Crvene stijene" on Mt. Romanija, and Nature Park Blidinje (Fig. 4).

Discussion

Distribution and range

Our comprehensive mapping efforts, resulting in a range of 5,014.36 km² (Fig. 2), significantly refine the known distribution of *D. mosorensis*. However, this value remains an underestimate, highlighting the need for further targeted surveys to fully delineate the species' range.

Croatia

Our thorough re-analysis, which was based on museum specimens, literature records, limited personal observations, and our survey, reveals a more restricted current presence in Croatia. Mt. Mosor (the type locality) (Kolombatović 1886) and Mt. Biokovo (Kolombatović 1895) remain the only confirmed locations.

Our numerous trips to Mt. Mosor and Mt. Biokovo indicate an altitudinal shift in the species' distribution.

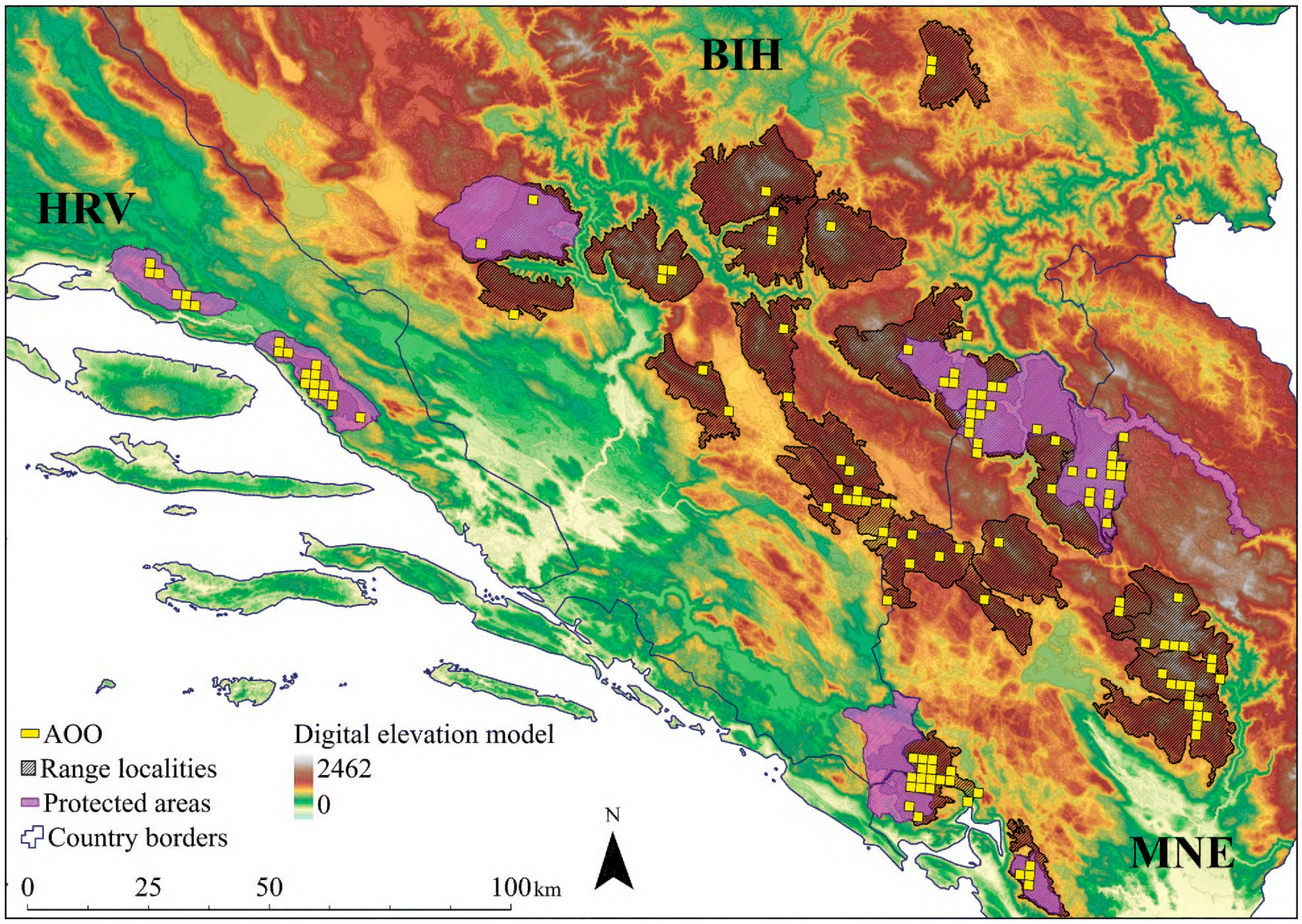

Figure 4. The map illustrates the overlap between the distribution of *D. mosorensis* and protected areas. The nature monument "Crvene stijene" on Mt. Romanija is not shown on the map due to its small size (15.10 ha).

Notably, despite the species being found at 750 m a.s.l. on Mt. Mosor in 2009 (Mekinić 2010), our lowest occurrence record for this species is 890 m a.s.l. from 2019. We observed that the species is especially abundant along the main ridge of Mt. Mosor at elevations of 900 m a.s.l. and above. The species' lowest recorded occurrence on Mt. Biokovo is at 931 m a.s.l. from 2023. Literature data state that the species is more abundant above 1,200 m a.s.l. (Schmidtler 1999); however, our recent research shows that 85% of occupied sites occur above 1,300 m a.s.l.

The species was documented on Mt. Kozjak in the 1950s (Hunt 1957), often cited as its westernmost known location, and on Mt. Opor in 1975 (Janev Hutinec et al. 2006). The latest IUCN evaluation considered Opor and Kozjak as a single location (Crnobrnja Isailović et al. 2024). Despite several surveys conducted across Kozjak (highest peak 779 m a.s.l.), including its northern slopes, we found no individuals. While suitable habitats and rocky terrain are present, questions persist regarding the species' historical existence. Schmidtler (1999) challenged Hunt's (1957) report of the species on Mt. Kozjak because of ecological inconsistencies and identification issues for several lizard species. We concur with Schmidtler's evaluation concerning the dubious identifications in Hunt's work. Furthermore, if the species was formerly extant on Mt. Kozjak, the mountain's modest altitude (779 m a.s.l.) and predominant southern exposure near the sea may have facilitated local extinction. We conclude that the species is no longer present in this area, and this locality should be excluded from discussions of its current range and distribution.

Mt. Opor (highest elevation 697 m a.s.l.) is the western extension of Mt. Kozjak. Our surveys at Opor indicated a lack of suitable habitats and rocks, with only dark-colored *Dalmatolacerta oxycephala* individuals observed. We believe the previous identification of *D. mosorensis* in Opor in 1975 was probably a misidentification, an uncertainty also confirmed by the observer (N. Tvrtković, pers. comm.). Therefore, this locality should also not be considered in the species' current range and distribution.

Two additional locations in Croatia have been reported but never reconfirmed (Jelić et al. 2015). These records originate from NHMW museum specimens, which reference the town of Sinj (NHMW, leg. Tomasini, 1907) (Džukić 1989; Janev Hutinec et al. 2006; Jelić et al. 2015) and Troglav (leg. et don. F. Kopstein, no. NMW 11652) (Jelić et al. 2015). It was incorrectly stated by Jelić et al. (2015) that the Troglav site was on the Croatia–Bosnia and Herzegovina border. Džukić (1989) initially identified the site as located between Bosnia and Herzegovina and Montenegro. Our verification of NHMW specimens and data supports their origins from Troglav in the border area of Herzegovina and Montenegro, as part of Mt. Somina, consistent with Džukić's designation.

The Sinj location continues to be one of the most enigmatic records. NHMW possesses three specimens collected by Tomasini in 1907 from this location. The city of Sinj is located in a valley at lower altitudes (approximately 320 m a.s.l.), on the southeastern edge of Mt. Svilaja. Our surveys in proximity to Sinj, encompassing Mt. Kamešnica (1,308 m a.s.l.) and Mt. Svilaja (1,508 m a.s.l.), revealed no evidence of *D. mosorensis*, despite the availability of suitable habitats. We also looked at all the reptiles that Tomasini had brought back to NHMW and confirmed that other species listed under Sinj, like *Lacerta viridis*, *Podarcis muralis*, and *Dalmatolacerta oxycephala*, do live on these two mountains. Further surveys are necessary to resolve this issue, given the higher altitudes of these locations, the northern position, and other correctly identified species.

Bosnia and Herzegovina

Among all three countries, *D. mosorensis* appears to have the most extensive range in Bosnia and Herzegovina, with additional localities awaiting confirmation. The existing literature data appear accurate, and the new data from this study have yielded insights that provide a better understanding of the species' distribution, which has expanded both northward and westward.

Northward expansion of the species' distribution and range was observed through new discoveries on Mt. Visočica, Mt. Bjelašnica, Mt. Treskavica, and Mt. Romanija. The most intriguing discovery was on Mt. Romanija, initially photographed by a mountaineer and later visited and reconfirmed, making this the northernmost location within the species' range.

Our discovery on Mt. Čvrsnica is particularly important, as it confirms the species' presence west of the Neretva River—a finding previously suggested by Šunje et al. (2014). Our discovery on Mt. Čvrsnica also supports the earlier finding west of the Neretva River noted in a personal comment by De Luca (Ljubisavljević et al. 2007a), which has not been brought up again. However, upon reviewing the literature, we found a record on Mt. Čabulja, Misirada Plateau, which is actually the first documented finding west of the Neretva River in Bosnia and Herzegovina (Lazar and Balent 2000).

The findings of *Dinarolacerta mosorensis* in Sutjeska and Rakitnica Canyons renew the suggestion that surveys of potential refugial habitats—such as gorges and canyons at lower elevations—should continue (Ljubisavljević et al. 2016). According to Stevens (2012), deep canyons, which may exhibit surface temperature inversion (Thompson 1967), frequently serve as both upstream and downstream corridors, linking low- and high-elevation terrains.

Podnar et al. (2014) stated that there are no clear past or present geographical barriers preventing gene flow, apart from deep valleys separating current mountainous populations. Our range map with its detailed range localities (Fig. 2) reveals potential distribution pathways and corridors above 1,000 m a.s.l., which extend from the Montenegrin mountains in the east into Bosnia and Herzegovina. There is a possibility that these areas, or at least neighboring locations, may not be fragmented.

The proximity of recent records in Montenegro indicates several potential localities, such as Mt. Volujak and Mt. Orjen. Other possible localities due to their proximity to known localities include Mt. Lelija (connected with Mt. Zelengora), Mt. Jahorina (between Mt. Romanija and Mt. Treskavica), and a continuation from Mt. Crvanj towards Mt. Lebršnik. The area positioned west of the Neretva River represents the most significant distribution gap towards Croatia and is thus a crucial area for future surveys. Possible localities in this gap include Mt. Vran (connected to Mt. Čvrsnica) and Mt. Ljubuša, which is a continuation of the mountain range from Mt. Vran towards the northeast, plus several mountains in the triangle between Mt. Kamešnica, Mt. Biokovo, and Mt. Čvrsnica. It is also essential to re-examine historical locations such as the Korito Plateau (800–1,100 m a.s.l.) and similar low-altitude sites to reconfirm the species' current presence, especially considering threats connected to climate change.

Montenegro

While some localities still require confirmation or detailed mapping, Montenegro stands out as the best-studied country concerning *D. mosorensis* distribution. Nonetheless, there are a few historical localities that need further clarification. One such location is Kameno, which Džukić (1989) places at 450 m a.s.l. (corresponding to the village's elevation), based on three specimens from the NHMW collection. However, the exact location name for these specimens is "Kameno b.", meaning Kameno hill. If we look at historical maps (Timár et al. 2010), Kameno hill is situated at elevations from around 600 to over 800 m a.s.l. Therefore, an elevation around 800 m a.s.l. is more accurate when discussing the original Kameno locality.

A doubtful record for *D. mosorensis* "above Cetinje" mentioned by Bischoff (1984) likely refers to the species' general distribution area extent from Split to Cetinje from Karaman (1921, 1939) and Pozzi (1966). While potentially indicating nearby Mt. Lovćen, this cannot be confirmed due to insufficient explanation in the older literature. Cetinje should therefore not be considered a valid site within the species' range. We reconfirmed Mt. Volujak, which had been omitted in the distribution study for Montenegro, and it is now the site with the highest known species elevation record at 2,031 m a.s.l., surpassing the previous record of 1,900 m a.s.l. at Mt. Durmitor (Ljubisavljević et al. 2016).

Consistent with findings in Bosnia and Herzegovina, the data and configuration of known range localities (Fig. 2) suggest additional sites in Montenegro where *D. mosorensis* could be present. These potential localities include Mt. Vojnik (near the Krnovo Plateau and Mt. Golija), Mt. Sinjajevina (between Mt. Durmitor and Mt. Moračke planine), and Mt. Ledenice (between Mt. Golija and Mt. Bioč). Another area worth exploring lies between Mts. Somina and Njegoš and Mt. Prekornica towards the Adriatic Sea. These regions likely served as important dispersal pathways for

D. mosorensis during different glaciation periods and may still hold its undiscovered populations. Additionally, we recommend paying special attention to all literature records at lower altitudes (such as Kameno brdo, Krivošije, etc.) to determine whether the species is still present in those areas.

The populations on Mt. Orjen and Mt. Lovćen appear fragmented from other known localities. Given their likely isolation from the main species range and their proximity to the sea under direct Mediterranean influence, we recommend continuous monitoring of these populations due to their potentially distinct conservation challenges.

Conservation status according to the Red List criteria

Global and European conservation status overview

Our results indicate a larger EOO (18,725.34 km²) and AOO (528 km²) compared to the last IUCN assessment (Crnobrnja Isailović et al. 2024). This increase is likely the result of additional findings in the north and west of Bosnia and Herzegovina and will likely increase further with continued mapping efforts.

The last IUCN assessment questioned whether the species was severely fragmented or restricted to 10 locations. Based on current distribution data, we tend to consider that the species occurs at more than 10 locations. There is evidence of fragmentation in the species' distribution, with some localities (Mt. Mosor, Mt. Biokovo, Mt. Orjen, and Mt. Lovćen) forming different subpopulations due to lack of a connection. Despite the lack of major geographic barriers, the Mt. Biokovo and Mt. Mosor populations show evidence of prolonged separation (Podnar et al. 2014). Connectivity between populations on the west and east sides of the Neretva River is also questionable (Bischoff 1984; Džukić 1991). The Neretva River represents a significant barrier to gene flow for many species, including *P. melisellensis* (Podnar 2004; Podnar et al. 2014) and *Dynaromis bogdanovi* (Krystufek et al. 2007). Fragmentation across the rest of the species' range is unclear. Considering altitude (< 1,000 m a.s.l.), populations from Mt. Prenj and Mt. Bjelašnica in Bosnia and Herzegovina to Mt. Durmitor and Mt. Prekornica in Montenegro may be connected (Fig. 2).

To date, only two phylogenetic studies have been conducted, analyzing specimens primarily from Montenegro (Ljubisavljević et al. 2007a; Podnar et al. 2014). Until future genetic or distribution studies indicate otherwise, each range locality from this study should be considered as a separate subpopulation or location according to IUCN criteria (IUCN Standards and Petitions Committee 2024).

We argue that climate change and its repercussions are the main threat to *D. mosorensis*. This is a cold-adapted species returning to its interglacial refugia (Podnar et al. 2014), which today are mostly higher elevations on mountaintops. Manes et al. (2021) predicted that mountain and island endemics face 84%–100% extinction risk by 2100. Montane lacertids are considered particularly vulnerable to rising temperatures, increasing aridity, and intensified competition from species better adapted to new thermal and hydric conditions (Garcia-Porta et al. 2019). Threats identified in the IUCN assessment have an unknown or minimal scope and severity (Crnobrnja Isailović et al. 2024). They appear to be local or country-specific and will be addressed below.

Although our estimates of EOO and AOO, derived using IUCN methodology, differ slightly from those in the latest IUCN assessment, this difference does not impact the species' Near Threatened classification at either the global or European level: NT B1ab(iii).

Country-specific conservation status overview

Croatia

The last national IUCN assessment in Croatia was conducted ten years ago (Jelić et al. 2015), and an update is recommended. Our data analysis reveals that Croatia accounts for < 2% of the global range, based on range localities polygons, which differs from the 10% reported in the IUCN assessment (Crnobrnja Isailović et al. 2024).

The estimated EOO is 143.45 km², and the AOO is 84 km². The IUCN assessment for Croatia suggests three locations for this species (Crnobrnja Isailović et al. 2024); however, our data considers only two: Mt. Mosor and Mt. Biokovo. We confirm a continuing decline in the quality and extent of the species' habitat, mainly due to the impacts of climate change. Differences in altitudinal distribution were observed on Mt. Mosor, where the species was found at lower altitudes merely 15 years ago (Mekinić 2010) but has not been observed there in several recent surveys. All of this confirms that the species' status in Croatia is EN B1ab(iii)+B2ab(iii), as assessed for the EU 27 (which includes only Croatia) (Crnobrnja Isailović et al. 2024).

There are several other discrepancies between our observations and the IUCN threats listed for Croatia (Crnobrnja Isailović et al. 2024). Over the past seven years, we found that human activity does not significantly impact *D. mosorensis* habitats and populations in Croatia. On Mt. Mosor, the only human presence in the species' habitats consists of mountaineers, as these are hard-to-reach areas. The road to the highest point on Mt. Biokovo attracts more visitors, but no roadkill was recorded. People on mountain trails are rare and do not seem to affect the species. Furthermore, since Mt. Mosor and Mt. Biokovo are part of the Natura 2000 ecological network, there are currently no plans for building large tourist resorts or establishing wind farms in areas inhabited by the species, as mentioned in the IUCN assessment. There is currently one wind farm on Mt. Mosor, but it is located at lower altitudes where the species is not present. If illegal construction of houses for tourism or personal use is taking place, it occurs at lower elevations unsuitable for the species. According to the IUCN assessment, wildfires reduce habitat quality (Crnobrnja Isailović et al. 2024), and fire-driven reptile declines have been documented (Santos et al. 2022). However, we did not observe direct mortality or changes in abundance during the 2017 wildfire on Mt. Biokovo. The affected high-altitude habitat

consists of rocky grasslands, which may offer some resilience to fire. Additionally, we observed that the grassland recovered quickly and individuals were still present on the rocks. These findings highlight the need for targeted research to provide science-based evidence on the impact of wildfires on *D. mosorensis*. Additional studies on habitat selection are also recommended to inform appropriate conservation management (Ljubisavljević et al. 2017).

Bosnia and Herzegovina

In Bosnia and Herzegovina, there is no national Red List for *D. mosorensis*; however, the Federation of Bosnia and Herzegovina has assessed the species as Vulnerable (Lelo et al. 2016). The calculated EOO is 5,773.34 km², while the AOO is 136 km². There are 16 known range localities, or separate locations, each with their own short-term threats. A decline in the quality and extent of its habitat due to climate change impacts is probably ongoing. In conclusion, we argue that the species should be considered Near Threatened (NT) B1ab(iii) in Bosnia and Herzegovina. While its EOO is less than 20,000 km² (the threshold for Vulnerable under criterion B1), and habitat quality is declining, the population is not severely fragmented, there are more than 10 locations, and subpopulations do not exhibit extreme fluctuations.

In Bosnia and Herzegovina, intensive grazing in mountain areas has been identified as a threat, as it may increase predation risk (Lelo and Vesnić 2011; Crnobrnja Isailović et al. 2024). However, during our surveys, no cattle were observed in *D. mosorensis* habitats, though they were present nearby. While grazing can have a negative impact on reptiles (Pafilis et al. 2013), its effect on petrophilous species remains largely unexplored. The impact depends on co-evolutionary adaptations between native reptiles and introduced species, as well as an ecosystem's area, fragility, isolation, and resilience (Pafilis et al. 2013).

Montenegro

The most recent national Red List assessment in Montenegro was conducted in 2023, categorizing *D. mosorensis* as Vulnerable VU B2ab(iii, v) (Jelić et al. 2023), though a detailed explanation is not available. The estimated EOO is 4,727.92 km², and the AOO is 308 km². There are 15 known range localities, or separate locations with their individual short-term threats. There is probably an ongoing decline in the quality and extent of its habitat due to climate change impacts. Therefore, although the national assessment was conducted recently, according to new IUCN guidelines available since 2024 (IUCN Standards and Petitions Committee 2024), we suggest that the species be considered Near Threatened NT under criteria B1ab(iii) + B2ab(iii). The justification for this is that while the EOO (B1) is less than 20,000 km² and the AOO (B2) is less than 500 km² (the threshold for category Vulnerable), the other conditions are not fully met. Specifically, although habitat quality is declining, the population is not severely fragmented, exists at more than 10 locations, and subpopulations do not exhibit extreme fluctuations. For Montenegro, we have no additional comments regarding the threats listed in the IUCN assessment (Crnobrnja Isailović et al. 2024).

Sympatric lizard species

It has been stated that *D. mosorensis* may be a weak competitor, as its occurrence is negatively correlated with the presence of all other lizards (D. Jelić pers. comm. 2023; as cited in Crnobrnja Isailović et al. 2024). Furthermore, it has been suggested that in Croatia, it seems to be restricted to higher areas without *Podarcis* species or *Dalmatolacerta oxycephala* (Jelić et al. in prep., as cited in Crnobrnja Isailović et al. 2024). This statement directly conflicts with literature and our field observations.

Sympatry between *D. mosorensis* and *D. oxycephala* was first observed on the Korito Plateau in the late 19th century (Tomasini 1889, 1894; Werner 1907; Arnold 1987) and later on Mt. Baba, Mt. Velež (Nevesinje), and Mt. Zelengora (our observation). Although sympatry between these two species was documented long ago, no research has studied their possible syntopy. Some data reveal differences in rock height and preference for more humid areas (Arnold 1987), suggesting differences in microhabitat use. In Croatia, we also observed differences in microhabitat use between *P. melisellensis*/*P. muralis* and *D. mosorensis* at sites where these species occur together in the same habitat. However, these are only observations and need to be studied further. Regarding *P. siculus*, the species has not yet been verified in Bosnia and Herzegovina, and we have never observed it occurring in syntopy with *D. mosorensis* in Croatia or Montenegro.

During our research, *D. mosorensis* was found syntopically with three lizard species on Mt. Mosor (*D. oxycephala*, *Algyroides nigropunctatus*, and *P. melisellensis*), two on Mt. Biokovo (*P. melisellensis* and *P. muralis*), and two on Mt. Orjen and Mt. Lovćen (*D. oxycephala* and *P. muralis*). On Mt. Prekornica, Mt. Moračke Planine, Mt. Bioč, Mt. Maglić, Mt. Volujak, and the Sutjeska canyons, it is found sharing habitat only with *P. muralis*. Also notable is that *D. oxycephala* is present on Mt. Biokovo and Mt. Prekornica but has never been detected syntopically with *D. mosorensis*. It was reported that *D. oxycephala* is distributed up to 1,050 m on Mt. Biokovo, while *D. mosorensis* is found above 1,200 m a.s.l. (Schmidtler 1999). Still, our highest new recorded observations for *D. oxycephala* at Mt. Biokovo are at 1,230 m a.s.l., without *D. mosorensis* present. On Mt. Prekornica, *D. oxycephala* occurs below 1,150 m a.s.l.

Although some species are expected to shift to higher altitudes (Garcia-Porta et al. 2019), using only species occurrence datasets may provide false impressions. Further research is needed to determine interspecific interactions in syntopy between small Lacertidae species and *D. mosorensis*.

Protected areas important for species conservation

Protected areas (PAs) are fundamental to biodiversity protection. Globally, between 88.1% and 91.8% of amphibian and reptile species have less than 30% of their range within

strictly protected areas, both currently and under future projections (Mi et al. 2023). The EU Biodiversity Strategy for 2030 acknowledges that the current PA network, including strictly protected areas, is insufficient to safeguard Europe's biodiversity in the face of multiple stressors (European Commission 2020). In Europe, while the Natura 2000 network and national protected areas (NPAs) protect many amphibians and reptiles, they often underrepresent narrow-range endemics, such as those found in the Balkan Peninsula and Mediterranean islands (Abellán and Sánchez-Fernández 2015).

Climate models project declining suitability of European PAs for many species during the 21st century. The Natura 2000 network is particularly vulnerable due to its flatland areas, where larger range losses are expected. In contrast, NPAs may offer more effective protection, partly because they are often situated in mountainous regions, which can act as climate refugia (Araújo et al. 2011). Already confined to its interglacial refugia (Podnar et al. 2014), *D. mosorensis* is particularly vulnerable to such future habitat shifts.

The existing PAs cover 44% of the known AOO of *D. mosorensis*, but the coverage varies by country. Bosnia and Herzegovina has the lowest coverage, with only 26% of occupancy grid cells protected, followed by Montenegro with 39%. In contrast, Croatia has 100% of its AOO grid cells within PAs. While all known range localities in Croatia are included in PAs, only 37.5% and 53% are included in Bosnia and Herzegovina and Montenegro, respectively. With more targeted research, the percentage of protected localities for *D. mosorensis* in Bosnia and Herzegovina, as well as in Montenegro, is likely to change.

According to the EU Habitats Directive, proposed Natura 2000 sites should cover 20% to 60% of a species' total population in a given biogeographical region. Protecting 60% should generally ensure Favorable Conservation Status (FCS) (The European Topic Center on Biological Diversity n.d.). As EU candidate countries, Bosnia and Herzegovina and Montenegro are expected to develop a Natura 2000 network in the future. Since the distribution of *D. mosorensis* in both countries lies within the Mediterranean and Alpine biogeographical regions, aiming for the highest possible percentage of protection in each region is strongly recommended.

Conclusion

This study significantly expands the known distribution of *D. mosorensis* by identifying nine new range localities. The newly discovered sites include Mt. Čvrsnica, Mt. Visočica, Mt. Bjelašnica, Mt. Treskavica, Mt. Romanija, Mt. Bioč, Mt. Moračke planine, and the Rakitnica and Sutjeska Canyons. Additionally, we reconfirm the species' presence on two mountains, Mt. Volujak and Mt. Čabulja, which were not included in previous distribution reviews. Our discoveries in canyons substantiate the notion that studies should encompass not just suitable habitats at high elevations but also potential refuge habitats in gorges and canyons at lower elevations. We extended the species' range further north and west of the Neretva River and identified distribution gaps in Bosnia and Herzegovina and Montenegro where *D. mosorensis* may be present. The highest recorded species occurrence is now at a new maximum of 2,031 m a.s.l. on Mt. Volujak.

Our findings support previous observations that *D. mosorensis* thrives at higher elevations (1,100–1,900 m), with its presence at lower elevations restricted to canyons and mountain slopes in the Adriatic hinterland. We argue that the range localities should be considered as separate locations according to IUCN criteria, as their connectivity remains uncertain. We are confident that the populations on Mt. Mosor and Mt. Biokovo, as well as Mt. Orjen and Mt. Lovćen, represent distinct and unconnected subpopulations.

We emphasize the necessity for further comprehensive investigation into the species' presence at lower elevations. Continuous monitoring is essential to determine if, and how quickly, the species is retreating from these areas, as our findings on Mt. Mosor suggest. It is critical to revisit all lower-altitude sites with historical records of the species' presence, like the Korito Plateau, Kameno Brdo, etc., as these are the initial areas where the species' survival is jeopardized due to climate change.

Establishing new protected areas (PAs) is fundamental for the conservation of this species, particularly in Bosnia and Herzegovina. However, it is equally crucial to intensify research efforts focused on this species. The Mosor Rock Lizard remains inadequately studied, with few exceptions in Montenegro. Climate change and related threats, along with scientists' predictions, do not suggest a positive future for this endemic and relict Dinaric species. Future research should focus on species distribution modeling, genetic studies, and ecological investigations to better understand population and habitat structures, fragmentation, interactions, potential threats, and interspecific relationships. These efforts will be crucial for developing effective, evidence-based conservation strategies to protect the species.

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Supplementary material 1

New and Literature Records of Dinarolacerta mosorensis in Croatia, Bosnia and Herzegovina, and Montenegro

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Data type: xlsx

Explanation note: contains all the data records from the literature and newly collected data used in the preparation of this paper. It also includes location names, range locality names, altitude, coordinates, coordinate origin, references, observer, and comments.

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